IEC 61788-24

Edition 1.0 2018-06

INTERNATIONAL STANDARD

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colour inside

Superconductivity –
Part 24: Critical current measurement – Retained critical current after double bending at room temperature of Ag-sheathed Bi-2223 superconducting wires

Supraconductivité –
Partie 24: Mesurage du courant critique – Courant critique retenu après double flexion à température ambiante des fils supraconducteurs Bi-2223 avec gaine Ag

IEC 61788-24:2018-06(en-fr)

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CONTENTS

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____

SUPERCONDUCTIVITY –

**Part 24: Critical current measurement –
Retained critical current after double bending at room temperature of Ag-sheathed Bi-2223 superconducting wires**

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The text of this standard is based on the following documents:

FDIS	Report on voting
90/402/FDIS	90/406/RVD

Full information on the voting for the approval of this International Standard can be found in the report on voting indicated in the above table.

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- reconfirmed,
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INTRODUCTION

In 1988, a new class of high critical temperature (T_c) copper oxide superconductors, Bi-Sr-Ca-Cu-O, was discovered. After nearly three decades, $(Bi,Pb)_2Sr_2Ca_2Cu_3O_x$ (Bi-2223) is now being utilized as a commercial high-T_c superconducting wire.

Superconducting wires are often subjected to bending deformation during production and application, e.g. during wire processing, magnet construction, cable fabrication, etc. The wire is bent towards both the upper and lower directions as it passes through several pulleys. These production processes are carried out at room temperature. Critical current of the wire is likely influenced through such bending, and may be accompanied by irreversible degradation in case of large deformation. The easiest way to evaluate the influence of bending on critical current is to carry out comparative measurement with the wire in the straight form before and after bending to a specific diameter.

After a wire is made into a coil or a cable, critical current is often measured under bending conditions or a more complex deformation state. In these cases, change in critical current may include both reversible and irreversible contributions depending on the amount of deformation. Irreversible degradation usually originates from a fracture in the superconducting component. In order to evaluate only irreversible contributions, measuring the retained critical current after the wire is straightened back from its deformed shape is necessary.

The critical bending diameter below which wire performance degrades significantly is typically specified for use of commercial superconducting wire. Thus, it is important to standardize measurement methods for the retained critical current after double bending. This document can be applied to other similar bending tests such as single bending, cyclic bending, etc.

This document consists of two fundamental technologies of the critical current measurement and the double bending process.

SUPERCONDUCTIVITY –

Part 24: Critical current measurement – Retained critical current after double bending at room temperature of Ag-sheathed Bi-2223 superconducting wires

1 Scope

This part of IEC 61788 describes a test method for determining the retained critical current after double bending at room temperature of short and straight Ag- and/or Ag alloy-sheathed Bi-2223 superconducting wires that have the shape of a flat or square tape containing mono- or multicores of oxides. The wires can be laminated with copper alloy, stainless steel or Ni alloy tapes.

The test method is intended for use with superconductors that have a critical current less than 300 A and an n-value larger than 5. The test to determine the retained critical current is carried out without an applied magnetic field, with the test specimen immersed in a liquid nitrogen open bath.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60050-815:2015, *International Electrotechnical Vocabulary – Part 815: Superconductivity* (available at http://www.electropedia.org/)

3 Terms and definitions

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3.1
double bending
bending in one direction to a certain diameter followed by the subsequent bending in the opposite direction to the same diameter

Note 1 to entry: Bending diameter is defined as the diameter of the bending mandrel.

Note 2 to entry: The definition of bending diameter is in principle the sum of the mandrel diameter and superconductor thickness. In the engineering process, however, the minimum diameter of the pulleys through which the wire is passed should also be considered.

3.2
constant sweep rate method
voltage-current data (U-I data) acquisition method where a current is swept at a constant rate from zero to a value above critical current (I_c) while continuously or frequently and periodically acquiring U-I data

3.3
ramp-and-hold method
U-I data acquisition method where a current is ramped to a number of appropriately distributed points along the U-I curve and held constant at each of these points while acquiring a number of voltages and current readings

4 Principle

The principle of the double bending method is described as follows. Critical current at 77 K under self-field shall be measured in a straight configuration with no mechanical strain. After measurement the specimen shall be warmed up to room temperature.

Hereafter, the specimen shall be bent in one direction to the specified diameter and then returned to the straight configuration. Successively, the specimen shall be bent in the opposite direction to the same diameter and returned to the straight configuration again.

Critical current of the specimen at 77 K under self-field shall be measured after double bending and straightening. The time interval between critical current measurements before and after bending should be as short as possible.

Critical current is determined from voltage-current (U-I) characteristic measured in a liquid nitrogen open bath under a constant pressure. Critical current is determined as the current at a specific electric field strength criterion (electric field criterion) (E_c), which corresponds to the voltage criterion (U_c) for a specified voltage tap separation.

5 Apparatus

5.1 General

The apparatuses required for the present test methods include the following:

- mandrels with necessary bending diameters;
- critical current measuring system.

5.2 Bending mandrel

Bending diameter shall be defined as the diameter of the bending mandrel. Bendable length shall be longer than the distance between the voltage taps.

5.3 Critical current measurement holder

The measurement holder is constructed from an insulating material.

Critical current may inevitably depend on the measurement holder material due to specimen strain induced by the difference of thermal contraction between specimen and holder.

The structure of the measurement holder shall be one which does not induce a local excess strain. The specimen strain induced by the difference of thermal contraction between specimen and holder during cooling from room temperature to 77 K shall be minimized to within ± 0,1 %. This thermal strain can be evaluated in cases where the thermal expansion coefficients of constituent materials are known. To minimize the thermal strain, the holder shall be constructed from material which has a thermal contraction similar to the specimen.

NOTE Recommended measurement holder materials are described in A.3.

5.4 Critical current measuring system

The apparatus to measure U-I characteristics consists of a specimen probe, an open bath of liquid nitrogen and a U-I measurement system.

The specimen probe, which consists of a specimen, a measurement holder and a specimen support structure, is inserted in the open bath filled with liquid nitrogen. The U-I measurement system consists of a direct current source, a recorder and necessary preamplifiers, filters or voltmeters, or a combination thereof.

A computer-assisted data acquisition system is recommended.

6 Specimen preparation and set up

6.1 Length of specimen

The length (L) of the specimen to be measured shall be determined as follows (see Figure 1):

$$L = 2 \times L_2 + 2 \times L_4 + L_1 + 2 \times L_3 > 5 \times W \quad (1)$$

$$L_1 \geq W,\ L_2 \geq W,\ L_3 \geq W \quad (2)$$

where

L_1 is the distance between the voltage taps;

L_2 is the length of the current contact;

L_3 is the shortest distance from the current contact to the voltage tap;

L_4 is the width of the voltage tap;

W is the width of the specimen to be measured.

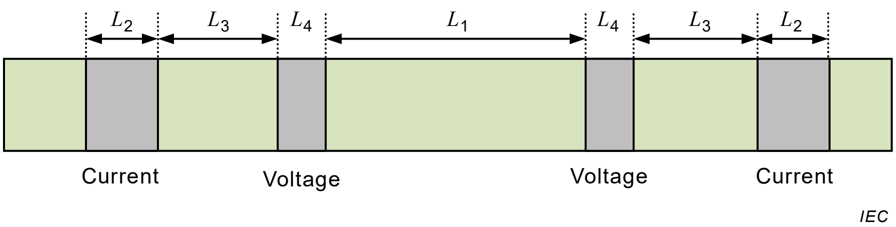

Figure 1 – Sample holder

For a specimen with a larger current-carrying capacity/width, L_2 shall be longer than $3W$. In cases where the specimen is laminated with stainless steel or laminated with another highly resistive material, L_2 shall be larger. For measurement which requires higher voltage sensitivity, L_1 shall be larger. In cases where current transfer voltage cannot be ignored, L_3 shall be larger.

In Table 2 of [1][1], five successful double bend test conditions are shown. Typically, specimen length L ranges from 90 mm to 150 mm, L_1 from 18,25 mm to 50 mm, L_2 from 10 mm to 20 mm, L_3 from 12,5 mm to 20 mm, and L_4 from 1,75 mm to 11 mm. When testing Bi-2223 wire with a stainless steel or nickel alloy laminate, L_2 should be sufficiently large to avoid local heating.

6.2 Mounting of the specimen

The specimen shall be mounted on the flat surface of the holder and both ends shall be fastened to the current contact blocks without solder, as described in A.3. As long as the current pad areas of the wire are not located within the area to be bent, they can also be soldered, if desired.

Voltage taps shall be placed in the central section of the specimen, without any material which cannot be removed.

NOTE The recommended voltage tap method is described in A.3.

The voltage leads shall be twisted as close to the voltage taps as possible.

7 Measurement procedures

7.1 Critical current measurement

Critical current shall be measured under conditions that avoid any extra mechanical strain.

The specimen shall be slowly immersed in the liquid nitrogen bath. The specimen shall be cooled from room temperature to the temperature of the liquid nitrogen over a time period of at least a few tens of seconds.

When using the constant sweep rate method, ramp rate shall be set so that I_c and n-value are not ramp rate dependent.

When using the ramp-and-hold method, current sweep rate between current set points shall be set lower than the equivalent ramping from zero current to I_c in 3 s. Data acquisition at each set point shall begin as soon as the flow/creep voltage generated by the current ramp can be disregarded. Current drift during each current set point shall be less than 1 % of I_c.

U-I characteristics are measured and recorded at increasing current values.

Baseline voltage of the U-I characteristic shall be determined as the recorded voltage at zero current for the ramp-and-hold method or the average voltage at approximately 0,1 I_c for the constant sweep rate method.

After measurement, the specimen shall be warmed up to room temperature.

7.2 Double bending

At room temperature, one end of the specimen shall be affixed to a mandrel of a specific diameter and the specimen bent along the mandrel from the fixed end to the free end, as shown in A.5.2. The bending section shall include the entire length between the voltage taps.

Hereafter, the specimen shall be free of bending.

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1 Numbers in square brackets refer to the Bibliography.

The specimen shall be turned over and reaffixed to the mandrel with the same diameter and bent along the mandrel from the fixed end to the free end of specimen.

Finally, the specimen shall be straightened.

7.3 Retained critical current after bending

Critical current shall be measured in a straight configuration with no mechanical strain other than straightening from the plastic deformation caused by the previous bending.

Critical current measurement shall be carried out using the same procedure as in 7.1.

Measurement shall be carried out in a liquid nitrogen open bath with a time interval between critical current measurements before and after bending treatment as short as possible. Since critical current is strongly dependent on temperature, attention shall be given to avoid variation in temperature before and after bending. A detailed discussion is provided in A.5.1.

8 Calculation of results

8.1 Critical current criteria

Critical current I_c shall be determined using electric field criterion E_c.

The value of I_c shall be determined under criteria of 100 µV/m and/or 10 µV/m.

I_c shall be determined to be the current corresponding to the point on the U-I curve where voltage U_c is measured relative to the baseline voltage (see Figure 2 and Figure 3):

$$U_c = L_1 E_c \tag{3}$$

where

U_c is the voltage criterion in microvolts (µV);

L_1 is the voltage tap separation in metres (m);

E_c is the electric field criterion in microvolts per metre (µV/m);

where U_c and I_c are the corresponding voltage and current values at the intersecting point of the straight lines with the U-I curve as shown in Figure 2.

A straight line shall be drawn from the baseline voltage to the average voltage near 0,5 I_c (see Figure 3). The finite slope of this line shall be due to current transfer and/or local sample damage. Valid determination of I_c requires that the slope of the line be less than 0,3 U_c/I_c, where U_c and I_c are determined under the criteria of 100 µV/m and/or 10 µV/m.

8.2 *n*-value (optional)

n-value shall be calculated as the slope of the plot of log U versus log I in the region between 100 µV/m and 10 µV/m.

9 Test report

9.1 Identification of test specimen

The test specimen shall be identified by the following:

a) name of the manufacturer of the specimen;

b) classification and/or symbol;

c) lot number.

9.2 Report of I_c values and/or retained I_c ratio

I_c values before and after bending and/or the retained I_c ratio, together with their corresponding criteria and n-values (optional), shall be reported.

9.3 Report of I_c test conditions

The following test conditions shall be reported as needed:

a) bending diameter (D);

b) fixing method of the current and voltage taps (for example, clip, crimping using Cu block, solder (for currents) or another connecting method);

c) length of specimen (L);

d) distance between voltage taps (L_1);

e) the shortest distance from a current contact to a voltage tap (L_3);

f) length of the current contacts (L_2);

g) sweep rate when using the constant sweep rate method;

h) ramp pitch, ramping time and holding time when using the ramp-and-hold method.

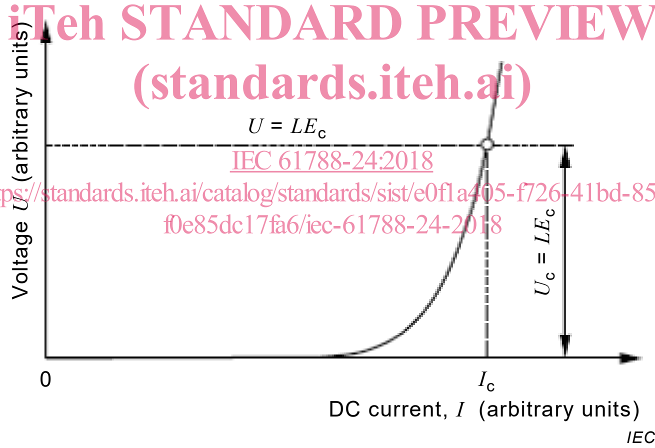

Figure 2 – Intrinsic *U-I* characteristic

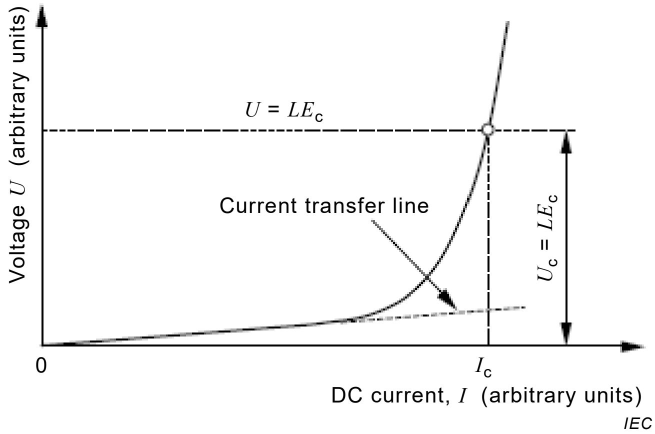

Figure 3 – *U-I* characteristic with a current transfer component

Annex A
(informative)

Additional information relating to Clauses 1 to 9

A.1 General

Many different variables have a significant effect on the critical current measurement value for Ag- and/or Ag alloy-sheathed Bi-2223 superconductor wires. However, significant portions of the test method covered in this document are common or similar to those for Bi-based oxide superconductors (IEC 61788-3 [2]). Only some of these variables are addressed in Annex A. For variables that are not mentioned here, refer to IEC 61788-3.

Special features of oxide superconductors can be classified into two groups. The first group is specific to oxide composite superconductors, including mechanical fragility, electromagnetic weak links, cryogen gas bubble formation, aging degradation, magnetic flux flow and creep, large anisotropy, hysteresis in critical current with magnetic field sweep, etc. The second group is related to the short length of the specimen used in the standard. Critical current measurement of such a specimen may easily pick up varying voltage signals due to thermal electromotive force, inductive voltage, thermal noise, current redistribution, specimen motion relative to the holder, etc. Current transfer voltages may be present due to the short distance from a current contact to the voltage tap.

Superconductors with critical currents above 300 A can be measured using this document with an anticipated reduction both in accuracy and precision and a more significant self-field effect.

Restrictions in this test method have been added in order to obtain the required precision in the final definitive phase of long conductor qualification.

A.2 Measurement condition

The minimum total length of the tape specimen is five times the tape width (W) plus two times the voltage tap width (L_4), which represents the sum of the following:

– the minimum voltage tap separation ($L_1 \geq W$);
– the length of the current contacts ($L_2 \geq W$);
– the shortest distance between the current and voltage contacts ($L_3 \geq W$).

A.3 Apparatus measurement holder material

In this method, the specimen strain is kept to a minimum (less than 0,1 %). A thermal contraction of less than 0,1 % does not result in an appreciable deviation of I_c at 0 T, near 77 K. One significant source of strain is the mismatch of thermal contraction rates between the measurement holder and the specimen when cooled to liquid nitrogen temperature.

Based on the typical thermal contractions shown in Table A.1, the following materials are recommended for the measurement holder material. For alternative holder materials, a carefully prepared qualification study should precede routine tests.

The recommended holder material is fibreglass epoxy composite, with the specimen lying in the plane of the fabric warp.